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SCHEDULING ATTACK SUBMARINE DEPLOYMENTS

by

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March 1997

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The Navy's peacetime mission is "to conduct forward presence operations to help shape the strategic environment by deterring conflict, building interoperability, and by responding, as necessary, to fast breaking crises with the demonstration and application of credible combat power." (OPNAV INSTRUCTION 3501.316, February 1995) The ability to carry out this mission hinges on the Navy's ability to maintain ships and submarines forward deployed in regions where such crises may occur.

The end of the Cold War and current budget constraints have caused a drawdown in the number of ships and submarines with which to provide forward presence. Coupled with the continued requirement to maintain a certain level of forward presence, this drawdown creates shortfalls when attempting to deploy ships or submarines to fill certain mission requirements.

To minimize these shortfalls, this thesis formulates the problem of scheduling attack submarine deployments as an integer program. Due to its size and complexity, heuristic algorithms are developed to provide near-optimal solutions in a reasonable amount of time. In addition to providing near-optimal deployment schedules, results from the algorithms are also useful in evaluating changes in maintenance and operational policies.

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SCHEDULING ATTACK SUBMARINE DEPLOYMENTS

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The reader is cautioned that computer programs developed in this research may not have been exercised for all cases of interest. While every effort has been made, within the time available, to ensure that the programs are free of computational and logic errors, they cannot be considered validated. Any application of these programs without additional verification is at the risk of the user.

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DEDICATION

I dedicate this thesis to my father, Jim Beckman. In the trying times of not only this project, but in everyday life, memories of him and his devotion to his work and family provide me the inspiration to fight on.

EXECUTIVE SUMMARY

The Navy's peacetime mission is "to conduct forward presence operations to help shape the strategic environment by deterring conflict, building interoperability, and by responding, as necessary, to fast breaking crises with the demonstration and application of credible combat power." (OPNAV INSTRUCTION 3501.316, February 1995) The ability to carry out this mission hinges on the Navy's ability to maintain ships and submarines forward deployed in regions where such crises may occur.

Over most of the past 30 years, the US has maintained 14 to 17 attack submarines deployed in forward areas. These forward deployed submarines have responded to numerous crises by providing a deterrence to aggressors and the application of force when necessary. Of the 181 crisis situations since World War II, attack submarines took part in 67. Only 6 of these 67 cases required a surge deployment of submarines from the continental United States. In all other cases, submarines already forward deployed were available to rapidly respond to the crisis. Forward deployment of attack submarines provides not only the demonstration of commitment and resolve to a region, but also the leading edge of crisis response.

The end of the Cold War and the fact that domestic budget requirements are beginning to outweigh those of the military have caused a drawdown in the number of submarines in the US Submarine Force. Not only are the submarine numbers decreasing, but the requirements for forward deployed submarines continue to increase due to the increasing number of third world crisis regions. With these two facts in mind, the US

Submarine Force will soon be unable to maintain its current forward presence which requires approximately 72 total attack submarines. The Navy currently has 79 attack submarines and this number is expected to decrease below the threshold of 72 in 1998.

For its part, the Submarine Force US Pacific Fleet (SUBPAC) maintains five to six attack submarines in forward areas around the Pacific Rim and as far west as the Indian Ocean. While in forward areas, these submarines may conduct various missions in addition to providing presence. With the expected reduction, efficient deployment scheduling becomes paramount if approximately the same level of presence or number of missions is expected of a smaller fleet.

At SUBPAC, the current scheduling method for attack submarine deployments is manual and typically conducted by the Schedules Officer. With up to three types of missions, the number of possibilities for deploying up to 35 attack submarines over a five year planning period is astounding. Human schedulers cannot be expected to select the best among all these possibilities. Currently, it takes the Schedules Officer up to a week just to find a feasible (let alone optimal) set of deployment schedules for the next five years.

As an aid to the SUBPAC Schedules Officer, this thesis presents an approach for scheduling Pacific Fleet Attack Submarines. This approach formulates the scheduling problem as an integer program. However, because of its complexity, the integer program is not solved to optimality. Instead, heuristic algorithms are used to obtain a nearly optimal schedule for SUBPAC in approximately 30 CPU seconds on an IBM RS6000 Model 590 workstation.

Specific advantages to the approach discussed in this thesis are:

1. It produces near-optimal deployment schedules which, in turn, improves efficiency in the employment of attack submarines.
2. It reduces the time to develop a schedule from up to a week to just a few hours.
3. It serves as a methodology for evaluating changes in maintenance and operating policies.
4. It provides a tool to rapidly modify current deployment schedules to accommodate unexpected events such as major equipment failures prior to a deployment.

I. INTRODUCTION

The Navy's peacetime mission is "to conduct forward presence operations to help shape the strategic environment by deterring conflict, building interoperability, and by responding, as necessary, to fast breaking crises with the demonstration and application of credible combat power." (OPNAV INSTRUCTION 3501.316, February 1995) The ability to carry out this mission hinges on the Navy's ability to maintain ships and submarines forward deployed in regions where such crises may occur.

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At SUBPAC, the current method for scheduling attack submarine deployments is manual and typically conducted by the Schedules Officer. With up to three types of missions, the number of possibilities for deploying up to 35 attack submarines over a five year planning period is astounding. Human schedulers cannot be expected to select the best among all these possibilities. Currently, it takes the Schedules Officer up to a week to find a feasible (let alone optimal) set of deployment schedules for the next five years.

A. PROBLEM STATEMENT

If SUBPAC is to be able to maintain the current level of presence or conduct the currently required missions, finding only a feasible set of deployment schedules may not be sufficient. To do just as much with less requires schedules that deploy submarines efficiently. The objective of this thesis is therefore to develop a methodology to aid the

Schedules Officer at SUBPAC in identifying a set of schedules that is not only feasible, but also best meets an acceptable level of forward presence. The technique used for this optimization problem is integer programming.

B. THESIS OUTLINE

Chapter II describes various facets of attack submarine operations. (Henceforth, the word 'submarines' refers to attack submarines.) In Chapter III, the deployment scheduling problem is formulated as an integer programming model. This chapter also describes preliminary results of using a commercial solver to obtain an optimal solution to the model. Chapter IV presents two heuristic algorithms for obtaining near optimal schedules, and Chapter V demonstrates how results from the deployment scheduling problem can be used to evaluate changes in maintenance and operating policies. Finally, Chapter VI concludes the thesis and offers recommendations for further studies.

II. SUBMARINE OPERATIONS

For the purpose of scheduling, a submarine is considered to be in one of three states: conducting shipyard maintenance, in work-up, or deployed. Between two consecutive shipyard maintenance periods, there is generally time for one or more deployments. However, prior to each deployment, sufficient time must be allowed for a submarine to (i) conduct necessary crew training and local operations, (ii) perform minor maintenance, and (iii) install and operationally test components necessary for the next mission. This preparation time prior to a deployment is referred to as a "work-up." In practice, crew training that does not require a submarine to get underway may be conducted while the submarine is in the shipyard. In this sense, a work-up may overlap shipyard maintenance. In the submarine community, some may differentiate between work-ups and local operations. However, such differentiation does not affect the deployment scheduling problem in this thesis.

The sections below describe each of these three states and other factors that may constrain the scheduling of submarine deployments.

A. SUBMARINE MAINTENANCE

To ensure the safety of a submarine and its crew, regular maintenance is necessary throughout the submarine's life, which is approximately 30 years. Maintenance requiring shipyard participation offers the least flexibility when determining available times to deploy a submarine. There are three types of shipyard maintenance: Selected Restricted Availability (SRA), Depot Modernization Period (DMP), and Refueling Overhaul

(ROH). These maintenance types are discussed below and graphically depicted in Figure 1.

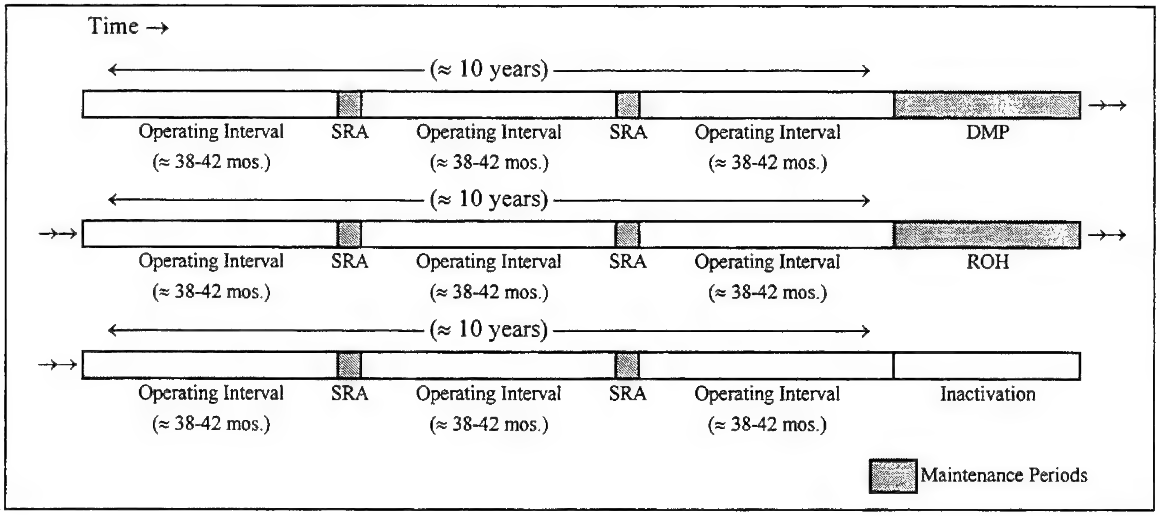

Figure 1 - Typical Shipyard Maintenance for a Submarine. A submarine typically conducts a Selected Restricted Availability (SRA) once every 38 to 42 months. A submarine must undergo a Depot Modernization Period (DMP) after 10 years of service and a Refueling Overhaul (ROH) after 20 years.

1. Selected Restricted Availability (SRA)

During a SRA, a submarine undergoes hull inspections to ensure its continued ability to safely operate submerged. These inspections require the ship to be in dry-dock, and any other maintenance requiring the submarine to be in dry-dock may also be conducted at this time. The time between two SRA's ranges between 38 and 42 months (see Figure 1), and each SRA lasts approximately three months (Pohtos, 1997). The time between any two SRA's, an SRA and another major maintenance period (i.e. DMP or ROH which are discussed below and shown in Figure 1), or time prior to ship's inactivation is called an operating interval. It is during these intervals that submarines may be deployed.

2. Depot Modernization Period (DMP)

Depot Modernization Periods are extensive refurbishments of a submarine. Major alterations to the ship's equipment and crew's living spaces usually take place during these periods, and the hull inspections discussed previously are also performed. A submarine enters a DMP after approximately its first ten years of operation, and each DMP lasts approximately 12 months (Pohtos, 1997).

3. Refueling Overhaul (ROH)

During a Refueling Overhaul, a submarine conducts all maintenance included in a DMP and refuels the nuclear reactor. ROH's occur after approximately 20 years of operation and can take up to two years to perform (Pohtos, 1997). After a ROH, a submarine remains in service for approximately ten years before decommissioning.

B. DEPLOYMENT MISSIONS

While maintaining forward presence around the world, attack submarines are also assigned to perform numerous types of missions. A few of their missions are described below.

1. Special Operations

The organic capability of a submarine to remain undetected makes it a prime candidate for covert insertion or extraction of special operations personnel. Special operations by US submarines are often carried out by the Navy's Sea-Air-Land teams (SEALs) who are trained for missions deep into enemy territory. Once inserted, these

special forces can conduct combat search-and-rescue operations or other clandestine high-risk missions. (SUBPAC Internet Homepage, 1996)

One capability of a submarine which makes special operations easier is the employment of a dry deck shelter (DDS). A DDS (a floodable pressure chamber piggy-backed on a submarine) is used for submerged delivery of personnel such as Marines or SEALs.

Figure 2 shows a submarine with a DDS attached. Although the DDS can be

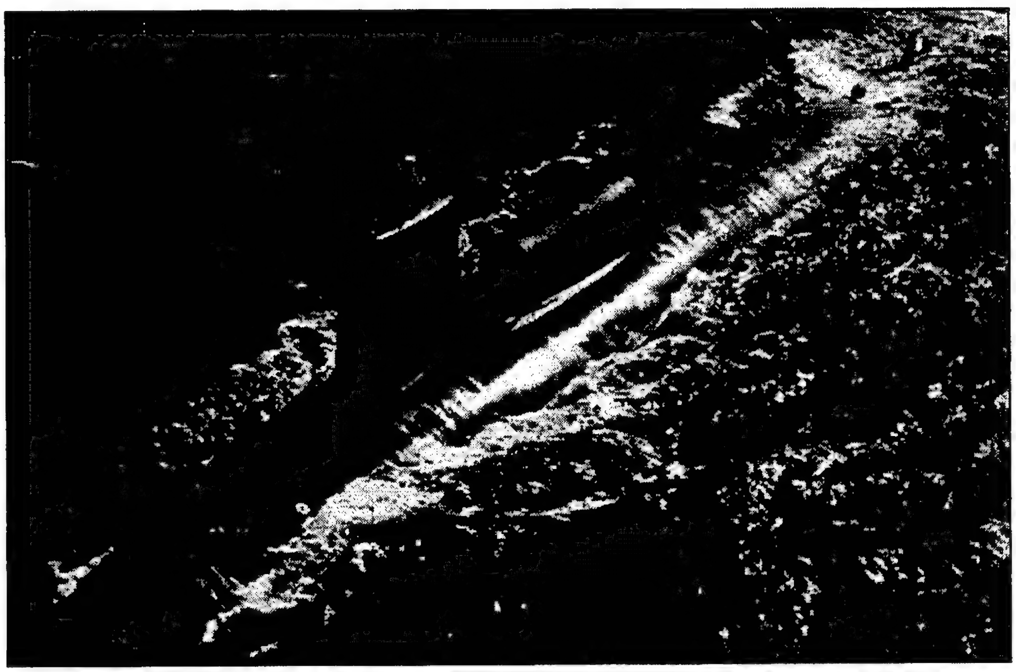

Figure 2 - A Submarine with a Dry Deck Shelter Attached

removed from one submarine and attached to another, not all submarines have the necessary equipment for the connection, thus submarines are specialized in this aspect.

2. Precision Strike

Some submarine missions require a Tomahawk Land Attack Missile (TLAM) strike capability. A TLAM strike is often used in situations where a carrier task force is unavailable or when the use of strike aircraft is deemed too risky. In fact during the Gulf War, US ships and submarines were the only forces to attack Baghdad during daylight due to the vulnerability of aircraft during this time. (SUBPAC Internet Homepage, 1996)

Although submarines are capable of launching TLAMs from their torpedo tubes, using a Vertical Launch System (VLS) is preferable. (See Figure 3) In this system, the

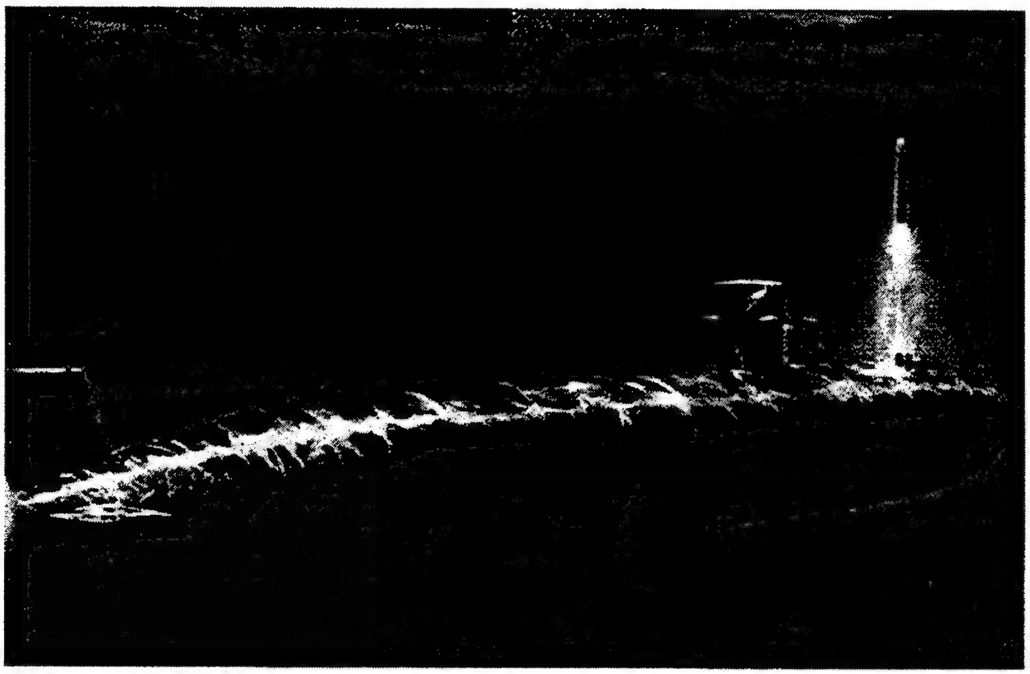

Figure 3 - Rendition of a Submarine Launching a Tomahawk Missile from a VLS

vertical launch tubes are external to the pressure hull of the submarine, thereby enabling a submarine to carry more TLAMs and, in turn, deliver more firepower. Because of this

increased firepower, a submarine fitted with a VLS is likely to be assigned to a precision strike mission. Approximately 35% of the SUBPAC submarines have been fitted with a VLS. (Pohtos, 1997 and Jane's Fighting Ships, 1996)

3. Surveillance and Intelligence

US submarines have been used for surveillance, intelligence and warning for the past 45 years. Unlike satellites and aircraft, submarines are not hampered by bad weather or cloud cover. In addition, submarines can remain on station almost indefinitely. The stealth characteristic of submarines allow them to enter an area to watch, listen, and collect information without being seen. With the ever changing military environment of the world, using submarines as a surveillance, intelligence and warning platform is a necessity for the future. (SUBPAC Internet Homepage, 1996)

4. Covert Mining

The stealth characteristic of a submarine allows it to transit into various areas and conduct mine-laying operations without any counterdetection by the enemy. This enables the US to render the enemy's sea lines of communication useless and therefore cutoff any possible resupply routes necessary for the enemy to fight adequately. To conduct mining operations, submarines must be properly equipped and undergo a certification process.

C. CONSTRAINTS ON DEPLOYMENTS

In addition to maintenance, the following also limit the availability of submarines for deployment.

1. Work-Up Periods

Prior to each deployment, various components of the submarine must be tested and the crew must be trained during a work-up period. The length of each period varies greatly between 12 to 20 months depending on the complexity of the upcoming mission. Some missions may require extensive crew training and possible installation of certain equipment on the submarine. The latter process may be very involved and require civilian technician expertise.

2. Tempo of Operations

To ensure reasonable operating conditions for naval personnel, the Chief of Naval Operations promulgates the following restrictions on ship deployment (OPNAV Instruction 3000.13A, 1990):

i. The maximum deployment length shall not exceed 6 months (181 days).
ii. The turn-around-ratio (TAR) must be at least 2 to 1. This means that, following the completion of a deployment, a submarine cannot commence another deployment for a time period that is at least twice the length of the last deployment.
iii. Each ship or submarine shall spend a minimum of 50% of its time in homeport over a five year period.

3. Other practices at SUBPAC

To allow submarines sufficient preparation time before entering dry-dock, SUBPAC submarines must return from a deployment at least three months prior to a scheduled SRA (Pohtos, 1996). After an SRA, a submarine should not be deployed for at least seven months (Pohtos, 1996). This time allows the submarine to conduct refresher training for the crew and also ensures sufficient time to discover and correct any

problems that may occur during or just after the SRA. Certain time constraints concerning DMPs and ROHs also exist, but these constraints vary significantly. Therefore, the time constraints for DMPs and ROHs are set to those of an SRA with the knowledge that more specific data it is easily incorporated in this research.

III. SCHEDULING SUBMARINE DEPLOYMENTS

Due to the limited shipyard capacity and the length of DMPs and ROHs, the maintenance schedules for submarines are fairly rigid and known at least five years in advance. Although small changes to the maintenance schedules occasionally occur due to unplanned maintenance or crises, these changes cannot be forecasted or scheduled a priori. For this reason, maintenance periods are assumed to be rigidly placed, but if any changes in the maintenance schedules should occur, they can be easily incorporated.

Given SUBPAC's practice of maintaining deployment lengths at six months (181 days), the key decisions in scheduling deployments consist of specifying for each submarine (1) when to commence deployments and (2) which mission to fulfill on each deployment. These two decisions, in turn, dictate the length of the work-up period prior to the deployment.

The first section below states assumptions and describes inputs necessary for formulating the scheduling problem as an integer program. Section B presents the formulation in detail and Section C relates it to formulations of similar problems already existing in the literature. Section D presents preliminary results when attempting to solve the problem optimally.

A. ASSUMPTIONS AND INPUT DATA

To reduce the number of decision variables to a manageable size relative to current computational technology, the five year planning horizon is divided into monthly intervals. Any events related to deployment scheduling are assumed to start at the

beginning and finish at the end of a month. Figure 4 shows a hypothetical maintenance plan for eight submarines. For example, the maintenance (an SRA in this case) for Submarine 6 starts on October 1, 1998 and ends on December 31, 1998.

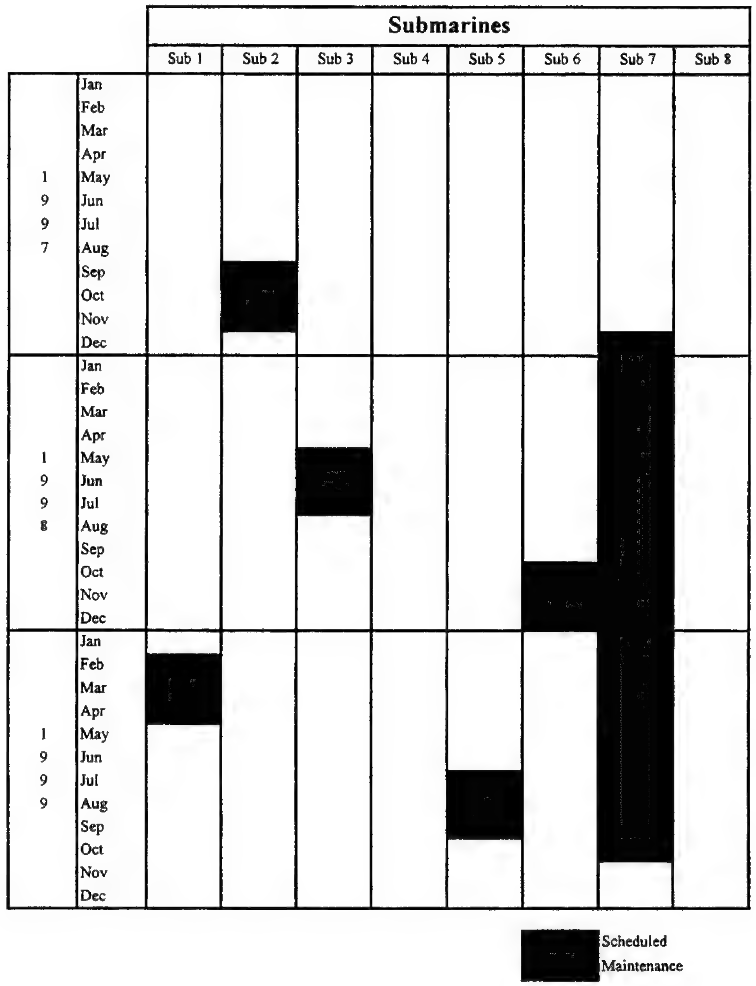

Figure 4 - Notional Maintenance Schedule for Eight Submarines

Other data significant to this problem are the capabilities of each submarine. With continual improvements and changes in design, submarines in the same class may not have the same capabilities. Submarines built later usually incorporate more

improvements and enhancements. While in maintenance, new equipment or components may be installed on a submarine, thereby endowing it with new capabilities. Each entry in Table 1 lists the types of missions that each submarine can perform over a planning period. For example, submarine 4 has the capability to perform missions 0 and II during January, 1997. Note that submarines 1 and 6 can perform one additional mission after their maintenance periods scheduled in Figure 4.

		Submarines							
		Sub 1	Sub 2	Sub 3	Sub 4	Sub 5	Sub 6	Sub 7	Sub 8
	Jan	0	0, III	0, II, III	0, II	0, I	0, III	0, I, II	0, II
	Feb	0	0, III	0, II, III	0, II	0, I	0, III	0, I, II	0, II
	Mar	0	0, III	0, II, III	0, II	0, I	0, III	0, I, II	0, II
	Apr	0	0, III	0, II, III	0, II	0, I	0, III	0, I, II	0, II
1	May	0	0, III	0, II, III	0, II	0, I	0, III	0, I, II	0, II
9	Jun	0	0, III	0, II, III	0, II	0, I	0, III	0, I, II	0, II
9	Jul	0	0, III	0, II, III	0, II	0, I	0, III	0, I, II	0, II
7	Aug	0	0, III	0, II, III	0, II	0, I	0, III	0, I, II	0, II
	Sep	0	0, III	0, II, III	0, II	0, I	0, III	0, I, II	0, II
	Oct	0	0, III	0, II, III	0, II	0, I	0, III	0, I, II	0, II
	Nov	0	0, III	0, II, III	0, II	0, I	0, III	0, I, II	0, II
	Dec	0	0, III	0, II, III	0, II	0, I	0, III	0, I, II	0, II
	Jan	0	0, III	0, II, III	0, II	0, I	0, III	0, I, II	0, II
	Feb	0	0, III	0, II, III	0, II	0, I	0, III	0, I, II	0, II
	Mar	0	0, III	0, II, III	0, II	0, I	0, III	0, I, II	0, II
	Apr	0	0, III	0, II, III	0, II	0, I	0, III	0, I, II	0, II
1	May	0	0, III	0, II, III	0, II	0, I	0, III	0, I, II	0, II
9	Jun	0	0, III	0, II, III	0, II	0, I	0, III	0, I, II	0, II
9	Jul	0	0, III	0, II, III	0, II	0, I	0, III	0, I, II	0, II
8	Aug	0	0, III	0, II, III	0, II	0, I	0, III	0, I, II	0, II
	Sep	0	0, III	0, II, III	0, II	0, I	0, III	0, I, II	0, II
	Oct	0	0, III	0, II, III	0, II	0, I	0, III	0, I, II	0, II
	Nov	0	0, III	0, II, III	0, II	0, I	0, III	0, I, II	0, II
	Dec	0	0, III	0, II, III	0, II	0, I	0, III	0, I, II	0, II
	Jan	0	0, III	0, II, III	0, II	0, I	0, I, III	0, I, II	0, II
	Feb	0	0, III	0, II, III	0, II	0, I	0, I, III	0, I, II	0, II
	Mar	0	0, III	0, II, III	0, II	0, I	0, I, III	0, I, II	0, II
	Apr	0	0, III	0, II, III	0, II	0, I	0, I, III	0, I, II	0, II
1	May	0, II	0, III	0, II, III	0, II	0, I	0, I, III	0, I, II	0, II
9	Jun	0, II	0, III	0, II, III	0, II	0, I	0, I, III	0, I, II	0, II
9	Jul	0, II	0, III	0, II, III	0, II	0, I	0, I, III	0, I, II	0, II
9	Aug	0, II	0, III	0, II, III	0, II	0, I	0, I, III	0, I, II	0, II
	Sep	0, II	0, III	0, II, III	0, II	0, I	0, I, III	0, I, II	0, II
	Oct	0, II	0, III	0, II, III	0, II	0, I	0, I, III	0, I, II	0, II
	Nov	0, II	0, III	0, II, III	0, II	0, I	0, I, III	0, I, II	0, II
	Dec	0, II	0, III	0, II, III	0, II	0, I	0, I, III	0, I, II	0, II

Table 1 - Capabilities of Submarines to Perform Missions 0, I, II, and III Over Time. Each entry lists the types of missions that each submarine can perform in the given month.

Of special note is mission 0 which represents the forward presence mission. In Table 1, every submarine is capable of performing mission 0. During this mission, the submarine is not required to perform any task in particular. The submarine only has to maintain presence in SUBPAC's areas of responsibility. In addition, submarines performing other missions are considered to be providing forward presence as well. When SUBPAC lists mission requirements, the requirement for forward presence usually subsumes those of others.

B. PROBLEM FORMULATION

The decision to deploy a submarine, s, at the beginning of a particular month, t, to perform a mission, m, is represented by the binary variable $Deploy_{m,s,t}$. Not all combinations of (m,s,t) are valid. The maintenance plan and submarine capabilities, in combination, determine which (m,s,t) combinations are valid. For example, Table 2 indicates the valid (m,s,t) combinations for submarine 6.

A number '1' in a particular row and column means that submarine 6 can deploy at the beginning of the indicated month to perform the indicated mission. For example, the number '1' in the first row and first column indicates that submarine 6 can deploy at the beginning of January, 1997 to perform mission 0. On the other hand, the number '0' in the row labeled February, 1998, signifies that submarine 6 cannot deploy at the beginning of that month. From Figure 4, submarine 6 must be in maintenance from the beginning of October, 1998, to the end of December of the same year. If submarine 6 is to deploy at the beginning of February, 1998, it will not be able to return three months

prior to the maintenance period in October as required by SUBPAC. Similarly, SUBPAC also requires submarines to be at homeport seven months after a maintenance period. Thus, the rows from January, 1999 to July, 1999 are set to zero. In Table 2, rows corresponding to three months before and seven months after the maintenance period for submarine 6 are lightly shaded. The dark shaded rows (October, 1998 - December, 1998) correspond to the maintenance period.

		Missions			
		Mission 0	Mission I	Mission II	Mission III
1997	Jan	1	0	0	1
	Feb	1	0	0	1
	Mar	1	0	0	1
	Apr	1	0	0	1
	May	1	0	0	1
	Jun	1	0	0	1
	Jul	1	0	0	1
	Aug	1	0	0	1
	Sep	1	0	0	1
	Oct	1	0	0	1
	Nov	1	0	0	1
	Dec	1	0	0	1
1998	Jan	1	0	0	1
	Feb	0	0	0	0
	Mar	0	0	0	0
	Apr	0	0	0	0
	May	0	0	0	0
	Jun	0	0	0	0
	Jul	0	0	0	0
	Aug	0	0	0	0
	Sep	0	0	0	0
	Oct	0	0	0	0
	Nov	0	0	0	0
	Dec	0	0	0	0
1999	Jan	0	0	0	0
	Feb	0	0	0	0
	Mar	0	0	0	0
	Apr	0	0	0	0
	May	0	0	0	0
	Jun	0	0	0	0
	Jul	0	0	0	0
	Aug	1	1	0	1
	Sep	1	1	0	1
	Oct	1	1	0	1
	Nov	1	1	0	1
	Dec	1	1	0	1

Table 2 - Valid (m,s,t) Combinations for Submarine 6. A number '1' in a particular row and column means that submarine 6 can deploy at the beginning of the indicated month to perform the indicated mission. A number '0' indicates that the submarine cannot deploy at the beginning of the month for that mission.

The numbers in column 3, which corresponds to mission II, are all zero. This is because submarine 6, according to Table 1, is not capable of performing mission II during the entire three year period. Similarly, except for the last five rows, the numbers in column 2 (or mission I) are all zero since submarine 6 will not have the capability to perform mission I until after the maintenance period starting in October, 1998.

Although Table 2 contains information useful for scheduling deployments, it does not take into account the necessary work-ups for these deployments. The length of a work-up period depends on the type of mission performed on the next deployment. Since no deployment has been scheduled, it is not possible to make the information in Table 2 more specific. In the formulation below, there is a constraint to ensure that a work-up period of the required length always precedes each deployment.

Below is an integer programming formulation of the submarine deployment scheduling problem. Information in Table 2 is represented as $\text{avail}_{m,s,t}$. This and other information required by the problem is listed under the heading "Data."

Indices:

t, t' = months (t = 1, 2, 3, ...T)

s = submarines (s = 1, 2, 3, ... S)

m, m' = mission types (m = 0, 1, 2, ...M where 0 = forward presence mission)

Data:

$$\text{avail}_{m,s,t} = \begin{cases} 1 \text{ if submarine } s \text{ can deploy at beginning of month } t \text{ to perform mission } m \\ 0 \text{ otherwise} \end{cases}$$

wu_m = length of workup period for mission m

$\text{req}_{t,\text{m}}$ = number of submarines required for mission m in month t

$\text{gappen}_{t,\text{m}}$ = penalty for each unfulfilled mission of type m in month t

d = length of a deployment

Variables:

$Gap_{t,m}$ = shortfall in fulfilling the requirement for mission m in month t

$$Deploy_{m,s,t} = \begin{cases} 1 \text{ if submarine } s \text{ deploys at beginning of month } t \text{ to perform mission } m \\ 0 \text{ otherwise} \end{cases}$$

Formulation:

$$\text{Min} \sum_{t=1}^{\text{T}} \sum_{m=1}^{\text{M}} \left(\text{gappen}_{t,\text{m}} Gap_{t,m} \right)$$

Subject to

$$\sum_{s=1}^{\text{S}} \sum_{t'=t-\text{d}+1}^{t} Deploy_{m,s,t'} + Gap_{t,m} \geq \text{req}_{t,m} \qquad \forall t, m \neq 0 \tag{1}$$

$$\sum_{m=0}^{\text{M}} \sum_{s=1}^{\text{S}} \sum_{t'=t-\text{d}+1}^{t} Deploy_{m,s,t'} + Gap_{t,0} \geq \text{req}_{t,0} \qquad \forall t \tag{2}$$

$$\sum_{m'=0}^{\text{M}} \sum_{t'=t-\text{wu}_m-\text{d}+1}^{t-1} Deploy_{m',s,t'} \leq \left(1 - Deploy_{m,s,t}\right)\text{wu}_m \qquad \forall m,s,t \tag{3}$$

$$\sum_{m=0}^{\text{M}} Deploy_{m,s,t} \leq 1 \qquad \forall s,t \tag{4}$$

$$Deploy_{m,s,t} \leq \text{avail}_{m,s,t} \qquad \forall m,s,t \tag{5}$$

$$Gap_{t,m} \geq 0 \qquad \forall t,m \tag{6}$$

$$Deploy_{m,s,t} \in (0,1) \qquad \forall m,s,t \tag{7}$$

The objective of the formulation is to minimize the weighted sum of all shortfalls in fulfilling mission requirements. Constraint (1) applies to all missions except forward presence (i.e., mission 0). The inner most summation sums $Deploy_{m,s,t'}$ over the index t' varying from t-d+1 to t. This accounts for the fact that, if a submarine is deployed at the beginning of month t' for mission m, it must still be on deployment filling mission m during month t. The outer summation then counts submarines that fulfill mission m in month t. If this sum is larger than $\mathrm{req}_{t,m}$ then $Gap_{t,m}$ equals zero, indicating that there is no shortfall in fulfilling mission m in month t. Otherwise, $Gap_{t,m}$ will equal the difference between $\mathrm{req}_{t,m}$ and the value of the nested summations. Constraint (2) is similar with the exception of the additional summation over index m to indicate that a submarine on deployment for any mission can be counted towards providing forward presence or fulfilling mission 0.

Constraint (3) ensures the required work-up is conducted prior to any deployment. If $Deploy_{m,s,t} = 1$, the right side of the constraint equals zero which, in turn, forces the decision variable $Deploy_{m',s,t'}$ to be zero for $t' \in (t\text{-}\mathrm{wu}_m\text{-d}+1,\ t\text{-}1)$ and for all m'. In words, if submarine s begins a deployment in month t to perform mission m, then its preceding deployment (to perform mission m') can begin no later than month t-wu_m-d. This is to allow a sufficient time for the submarine to return from its preceding deployment (for mission m') and complete the necessary work-up for the next deployment (for mission m). Note that the construction of $\mathrm{avail}_{m,s,t}$ guarantees that deployments terminate at least three months prior to and begin at least seven months after a maintenance period.

Constraint (4) prevents a submarine from being deployed for two different missions in the same month, and Constraint (5) eliminates invalid (m,s,t) combinations. (Note that in GAMS (Brooke et al, 1992), Constraint (5) can be implemented via the dollar operator instead of a constraint thus reducing the number of binary variables created.) Constraint (6) requires all gaps be positive, and Constraint (7) restricts the decision variable $Deploy_{m,s,t}$ to be binary.

Among data listed in the above formulation, $\text{gappen}_{t,m}$ is the only one not determined by operational requirements. Values for $\text{gappen}_{t,m}$ should reflect the importance of different missions during each month of the planning period.

C. LITERATURE SURVEY

In the literature, there are three approaches for solving deterministic scheduling problems of this type. The first approach formulates the problem as a set covering problem whose columns represent deployment schedules generated a priori or during a solution procedure. The second approach is based on a shortest path formulation. Finally, the third approach formulates the problem as an integer program.

Winston (1991, p 469) and Schrage (1991, Chapter 6) provide descriptions of the set covering approach. Brown, Goodman, and Wood (1990) use this technique in scheduling the deployments and exercises of Naval ships in the Atlantic Fleet. Stone (1990) also implemented the set-covering approach to schedule deployments of Atlantic Fleet aircraft carriers. With respect to submarine deployments, the set-covering approach is prohibitive due to the enormous number of potentially good schedules to consider.

Schauppner (1996) formulates the problem of scheduling aircraft carriers in the Pacific Fleet as a shortest path problem with side constraints. This approach appears to work well because carriers only have one type of mission to perform.

Ronen (1983 and 1993) reviews approaches to scheduling commercial ships. When the objective is to simply meet specific requirements instead of minimizing cost or maximizing profit, the scheduling problem is often formulated as an integer program that is solved either optimally or via a heuristic algorithm. Brown, Dell, and Farmer (1996) describe an application of a mixed-integer linear program used in scheduling United States Coast Guard cutters. Similar to the submarine scheduling problem, the US Coast Guard has multiple missions to perform. However, unlike submarines, every cutter can perform all types of missions. In addition, there are no required work-ups prior to any deployment, and maintenance is more flexible.

D. PRELIMINARY RESULTS

To validate the formulation of the deployment scheduling problem in the above section, five sets of input data were generated. These input data correspond to small, but realistic, scheduling problems. The planning horizon for these problems is approximately 2.5 years and they contain from 8 to 14 submarines. (These problems are roughly half the size of the real scheduling problem at SUBPAC.) Work-up periods with realistic lengths are used and maintenance periods are staggered so that they do not overlap excessively. The penalty of unfulfilled missions is set to 1 for all mission types.

To obtain optimal deployment schedules, the submarine deployment scheduling problem was implemented in the General Algebraic Modeling System or GAMS (Brooks et al., 1993) on an IBM RS6000 Model 590 workstation. The resulting integer program was solved using commercial software called CPLEX (CPLEX, 1994). CPLEX was set to terminate when it finds a solution known to have an objective function value within 5% of a truly optimal solution.

Table 3 summarizes the results from the five test problems. Problems 3 and 4 only differ by two submarines. However, the difference in the number of iterations and CPU time is quite large. The results for problem 5 also demonstrate that increasing the length of the time horizon of problem 4 from 30 months to 35 months makes the problem impossible to solve in a reasonable amount of time, e.g., no more than 48 hours.

Problem	Time Horizon (months)	Number of Subs	Variables		Number of Eqns.	Optimality Gap	Number of Iterations	CPU Time (secs)
			Cont.	Disc.				
1	20	8	81	198	810	0.025	129	1
2	25	10	101	380	1,346	0.036	13,831	55
3	30	12	121	466	1,919	0.046	18,274	64
4	30	14	121	550	2,197	0.050	493,708	1,717
5	35	14	141	629	2,597	N/A	6,160,494	N/A

Table 3 - Results of Preliminary Runs of Model

In summary, Table 3 suggests empirically that a realistic submarine deployment scheduling problem is difficult to solve to optimality. The next chapter proposes and compares two heuristic algorithms for obtaining nearly optimal solutions.

IV. HEURISTIC APPROACHES TO SCHEDULING

This chapter describes two heuristic algorithms for obtaining a near-optimal solution to the submarine deployment scheduling problem presented in the last chapter. The key idea in both algorithms is to decompose the original problem into problems of smaller size. Solutions to these smaller problems collectively yield a solution to the original problem. The first algorithm, the mission decomposition heuristic, decomposes the original scheduling problem with k types of missions into k subproblems; each subproblem schedules deployments for only one type of mission. In the literature, this approach has been used to decompose multicommodity network problems (e.g., Bertsekas and Gafni, 1982).

The other algorithm, the cascading time heuristic, decomposes the original problem temporally into a collection of subproblems; each subproblem schedules deployments to fulfill all mission requirements during a small segment of the planning period. This approach has been used to solve optimization problems with staircase structure (Baker, 1997).

The last section of this chapter compares these two heuristic algorithms.

A. MISSION DECOMPOSITION HEURISTIC

As stated earlier, submarines performing other missions are considered to be providing forward presence as well. Because of this practice, SUBPAC's forward presence (mission 0) requirement always includes those of others. For example, if SUBPAC states that it requires 10, 1, 2, and 3 submarines to perform missions 0, 1, 2,

and 3, respectively, in January of 1998, then the six submarines performing the three non-presence missions also count as providing forward presence. Therefore, SUBPAC only needs to schedule four submarines for mission 0. This section regards the requirement for four submarines (instead of ten) as the "pure" forward presence requirement.

The basic idea of the mission decomposition heuristic is to schedule deployments for each type of mission one at a time in some sequence. When scheduling deployments of the first type of mission in the sequence, all submarines capable of fulfilling the mission are considered. For each mission that follows, only submarines that have not been scheduled for missions examined earlier in the sequence can be considered. Note that the deployment scheduling problem with only one mission is easier to solve than problems with multiple missions. The formulation of the problem with one mission is a special case of the one presented in Chapter III.

If there are k types of missions, then there are $k!$ possible sequences for scheduling the missions one type at a time. Since the "pure" forward presence mission is unique, this thesis only considers the sequences that schedule the "pure" forward presence missions first. This reduces the number of possible sequences to $(k\text{-}1)!$. When all $(k\text{-}1)!$ sequences are solved, that sequence producing the best solution is retained as the final solution to the scheduling problem.

The main disadvantage of the mission decomposition heuristic is that it does not anticipate requirements later in the sequence. For example, if in addition of being capable of performing mission I, submarine 6 is the only submarine that can perform mission IV. Then, mission IV can go unfulfilled, if mission I is considered earlier than

mission IV in the sequence. However, by considering (nearly) all possible sequences, this effect is lessened, but not eliminated.

B. CASCADING TIME HEURISTIC

It is natural to also consider the planning period as consisting of Y years. In the cascading time heuristic, (Y-1) deployment scheduling subproblems are solved in sequence and each has a planning period of two years. The first subproblem schedules deployments for years one and two. Then, the deployment schedules that begin in year one are kept as a permanent part of the schedules for the entire Y years. (See Figure 5)

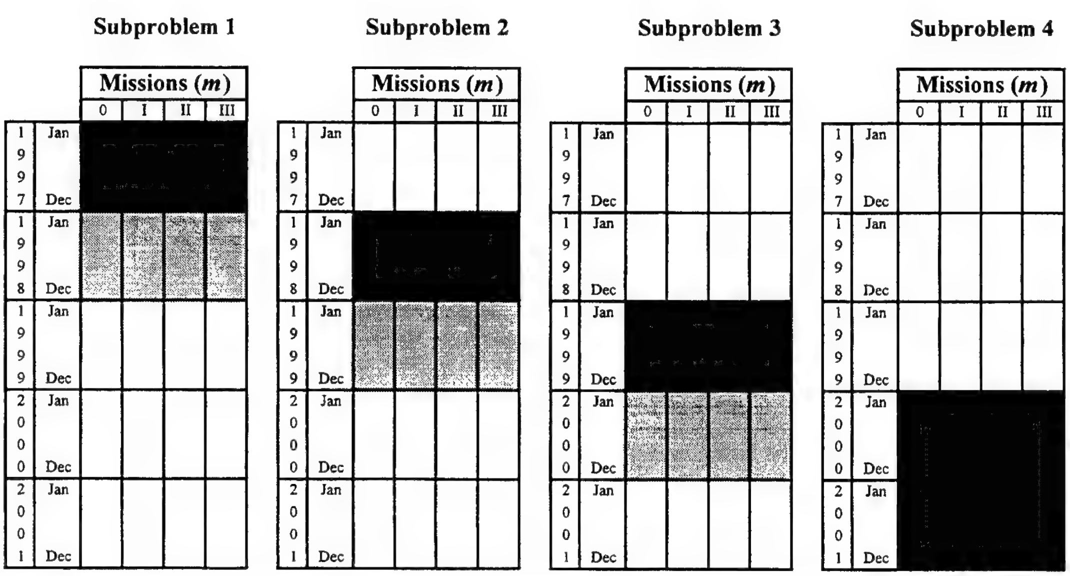

Figure 5 - Graphical Depiction of Cascading Time Heuristic. Deployments scheduled to begin in the dark shaded areas are kept as a permanent part of the final solution. Deployments beginning in light shaded areas are ignored and overwritten by the subsequent subproblem's solution.

The first subproblem's solution for deployments beginning in the second year is ignored. Next, the deployment scheduling subproblem for years two and three is solved. Schedules that begin in year two are kept as a permanent part of the schedules for the entire Y years and those that begin in year three are discarded. This process continues until the deployment scheduling subproblem for years (Y-1) and Y is solved. The last subproblem's schedule is kept as permanent.

In each successive scheduling subproblem, the schedules that begin in the second year of the two year planning period are discarded, thus not as important as those that begin in the first year. This suggests the penalty for shortfalls for the second year should be smaller than the one in the first year.

To empirically determine the best penalties for shortfalls in the first and second year, four submarine deployment scheduling problems are considered. In problem 1, there are 35 submarines to be scheduled over a five year planning period. Other data for problem 1 are listed in the Appendix. In problems 2, 3, and 4, there are 32, 28, and 25 submarines to be scheduled and other data are the same as problem 1. In all four problems, the penalties for unfulfilled missions in the first year are set to one. For the second year, they are set to 0.25, 0.50, 0.75, and 1.00. Table 4 summarizes the results on the four problems with various gap penalties. From this table, the penalties of 1.00 and 0.25 yield the smallest number of unfulfilled missions on average. In fact, this pair of penalties provides the best solutions for problems 1, 3, and 4. For problem 2, the pair of penalties gives a solution that is only 12% above the best solution in Table 4.

First Year Gap Penalty	Second Year Gap Penalty	Problem	Total Gaps In Mission Fulfillment
1.00	0.25	1	3
		2	56
		3	105
		4	145
		Average	77
1.00	0.50	1	16
		2	50
		3	112
		4	164
		Average	86
1.00	0.75	1	20
		2	55
		3	113
		4	158
		Average	87
1.00	1.00	1	23
		2	66
		3	131
		4	187
		Average	102

Table 4 - Results of Cascading Time Heuristic with Various Penalties for Unfulfilled Missions

Similar to the mission decomposition heuristic, cascading through time does not allow the algorithm to anticipate future requirements. The heuristic does not allow deployments already scheduled in previous subproblems to be moved forward or backward, even though doing so may enable more deployments to be scheduled.

C. COMPARING THE TWO HEURISTICS TO OPTIMAL SOLUTIONS

Table 5 compares the solutions produced by the two heuristics against solutions that are guaranteed to be within 5% of an optimal solution. Eight scheduling problems are solved. Each has to schedule 14 submarines to perform four types of mission over a

three year planning period. One of the four missions is for forward presence. For each month, the requirement for the forward presence varies between four and six submarines. Requirements for other missions are either one or two. For each problem, maintenance schedules and submarine capabilities are manually generated in a random manner.

On every problem, the cascading time heuristic generates better solutions than the mission decomposition heuristic. When compared to the solutions that are within 5% of optimality, the cascading time heuristic produces solutions with 28% more unfulfilled missions on average.

	Solution Within 5% of Optimality	Mission Decomposition		Cascading Time	
Problem	Missions Unfilled	Missions Unfilled	% Above Optimal	Missions Unfilled	% Above Optimal
1	65	122	87%	66	2%
2	57	116	104%	66	16%
3	24	74	208%	34	42%
4	16	46	188%	23	44%
5	18	50	178%	23	28%
6	21	58	176%	28	33%
7	20	72	260%	20	0%
8	9	26	189%	14	56%
		Average	173%	**Average**	28%

Table 5 - Comparison of the Two Heuristics Against Solutions within 5% of Optimality

V. RESULTS AND APPLICATIONS

In this chapter the cascading time heuristic with the first and second year penalties set at 1.00 and 0.25 respectively, is used to generate submarine deployment schedules for SUBPAC. To illustrate possible applications, the heuristic is also used to investigate impacts on fulfilling mission requirements due to changes in submarine force structure or operating policies.

A. GENERATING SUBMARINE DEPLOYMENT SCHEDULES

To validate both the model in Chapter III and demonstrate the quality of the schedules, the scheduling problem from SUBPAC was solved by the cascading time heuristic. The SUBPAC scheduling problem encompasses the period from January, 1997, to December 2001.

Thirty five submarines are to be scheduled to perform four types of mission, one of which is the forward presence mission. The requirements for non-presence missions vary between zero and two submarines per month. During the planning period, SUBPAC requires six submarines for forward presence in every month. This implies that the "true" forward presence requirement (defined in Chapter IV) in each month ranges from zero to six, depending on the requirements for the others. Work-up periods for missions 0 (forward presence), I, II, and III are 12, 18, 20, and 17 months, respectively. Specifics about these data are contained in the Appendix.

As before, the cascading time heuristic is implemented in GAMS and the two-year scheduling subproblem is solved by the CPLEX solver on the IBM RS6000 Model

590 workstation. For the SUBPAC scheduling problem, 30 CPU seconds were required to produce a feasible solution with a shortfall of three submarine months. SUBPAC requires six submarines for forward presence in December 2001, but the heuristic only supplies five. For the other two shortfalls, SUBPAC requires two submarines for mission II in May and June of 2001. The heuristic only supplies one submarine in each of these two months. The fact that these shortfalls occur in the last year of the planning period, although expected, is encouraging, in that all of the missions near the present are all filled. Since requirements in the distant future may change, the impact of the unfilled requirements in 2001 may not be as significant as they would be in earlier years.

To demonstrate that the cascading time heuristic produces a feasible set of schedules, Table 6 lists some of the operating parameters that may be of concern to the SUBPAC scheduler. In particular, Table 6 shows that, in the heuristic solution, all submarines return to homeport at least three months before and deploy at least seven months after a maintenance period. In addition, the heuristic also ensures that there is sufficient time for work-ups for all types of missions.

	Operational	**Heuristic Solution**	
	Requirements	**Minimum**	**Average**
Time in Homeport:			
Before Maintenance Period	3	3	6.0
After Maintenance Period	7	7	9.4
Time Available for Work-Up:			
Mission 0	12	12	14.2
Mission I	18	18	22.1
Mission II	20	20	25.8
Mission III	17	17	19.3

Table 6 - Comparing the Heuristic Solution to Operational Requirements

B. CHANGE IN SUBMARINE FORCE STRUCTURE

To analyze the effect of reducing the size of the submarine force structure at SUBPAC, the scheduling problem in Section A is resolved by the cascading time heuristic with two, four, or six submarines decommissioned as they are scheduled to undergo a shipyard maintenance. Thus, this represents reduction in force size beyond what is planned currently. The impact of these reductions is graphically depicted in Figures 6 and 7.

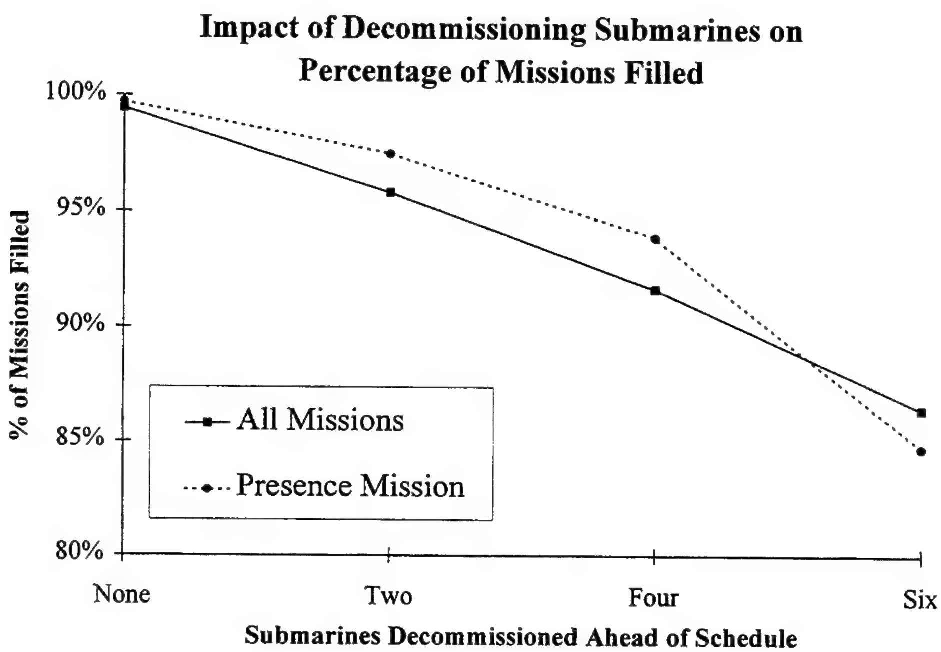

Figure 6 - Impact of Decommissioning Submarines on the Percentage of Missions Filled

The solid line in Figure 6 shows the percentage of fulfilled requirements averaged over all mission types. From this graph, the ability to fulfill the requirements decreases by approximately five percent for every two submarines decommissioned early. On the

other hand, the impact on the forward presence (the dotted line) when the number of submarines decommissioned is increased from four to six seems to be more significant than others.

For completeness, Figure 7 displays the impact of the decreasing force structure on the remaining missions. Although total mission fulfillment decreases monotonically as decommissioning increases (see Figure 6), Figure 7 shows an inconsistent trend in fulfillment of individual missions. This is due to the fact that all missions have equal penalty weights. (Note: the abstraction of classified data necessitates this fact.) This, in turn, creates multiple optimal and near-optimal solutions, any of which can be chosen by

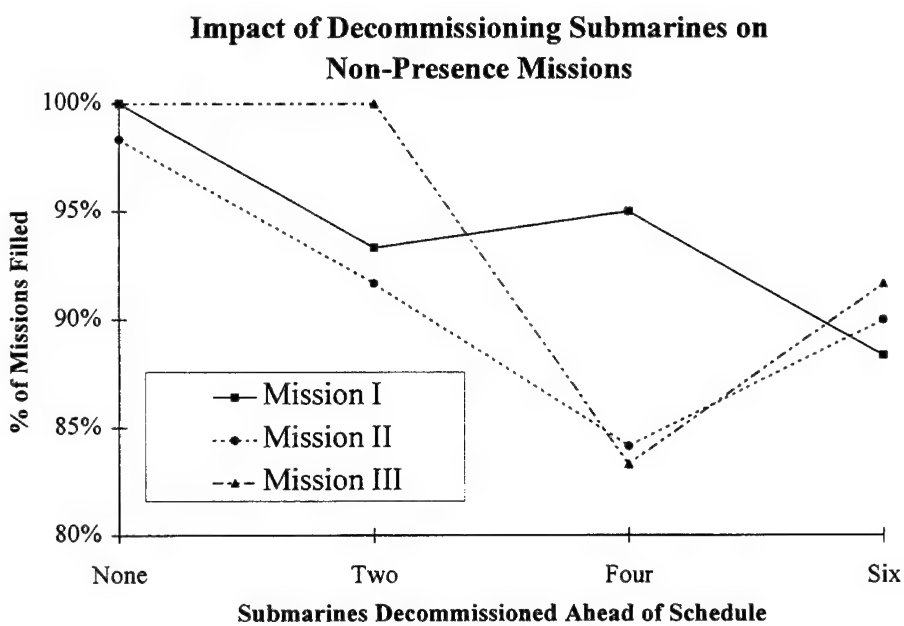

Figure 7 - Impact of Decommissioning Submarines on Non-Presence Missions

the heuristic. The impact on non-presence mission fulfillment will depend on which solution is chosen. Application of differing penalty factors will create more consistent behavior in mission fulfillment for non-presence missions.

C. CHANGES IN WORK-UP LENGTHS

Assuming that six submarines are to be decommissioned earlier than planned as described in the previous section, one alternative for fulfilling the required missions with fewer submarines is by increasing their availability. One such method is to reduce the length of work-up periods. Figure 8 shows the impact on mission fulfillment when individually decreasing the length of work-up periods for missions I, II, and III, by one month. From this figure, decreasing the length of mission I's work-up by one month

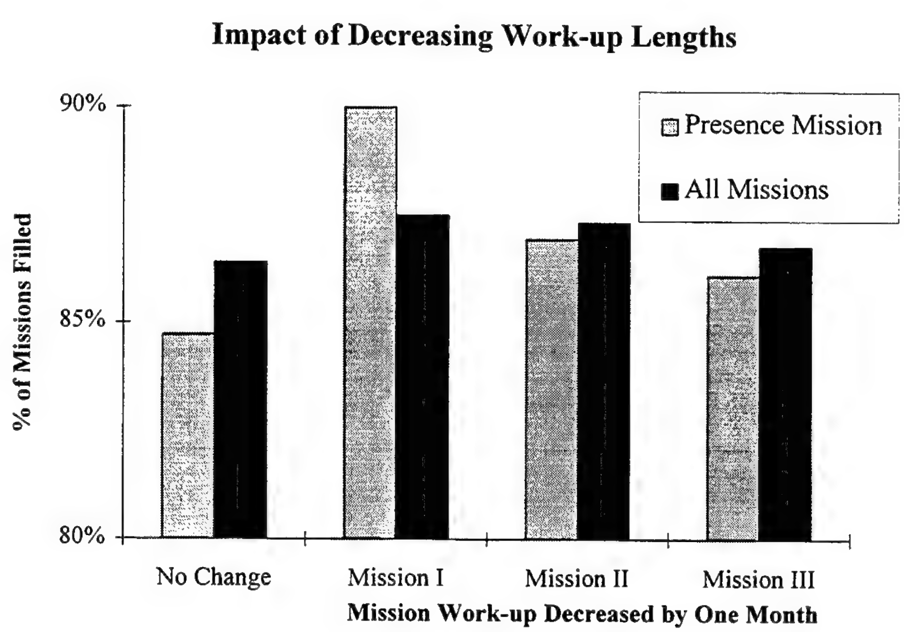

Figure 8 - Impact of Decreasing Work-up Lengths on Missions Filled

yields a 5% increase in forward presence, the best among the three non-presence missions. A five percent increase in filling the presence missions is significant, this equates to 18 months of deployed submarine time during the five year planning period—a significant amount of forward presence.

VI. CONCLUSIONS AND RECOMMENDATIONS

In this thesis, the problem of scheduling attack submarines for deployment at SUBPAC is formulated as an integer programming model. To obtain a near optimal solution in a reasonable amount of time, two heuristic algorithms, mission decomposition and cascading time heuristics, are considered. Of the two heuristics, the cascading time heuristic performs better empirically and is used to generate submarines deployment schedules for 35 submarines over a five year period in approximately 30 CPU seconds. It is also demonstrated that the generated schedules are operationally feasible and meet all mission requirements except for three months out of the entire five years for this example.

The cascading heuristic is also used to quantify the impact of changes in maintenance and operating policies. Two examples are considered. One examines the effect of reducing the submarine force structure by decommissioning submarines earlier than planned. The other examines the effect of decreasing the time required for work-ups.

In summary, this thesis demonstrates that the cascading time heuristic not only produces good submarine schedules quickly, but it also serves as a tool to analyze the impact of changes in policies governing the submarine operations at SUBPAC. In addition, this thesis also identifies several areas for future research.

1. In this thesis, the maintenance periods for all submarines are determined a priori. However, they have a significant impact on the availability of submarines for deployments. Badly planned maintenance periods would severely limit the ability for submarines to fulfill their missions. Thus, it is

important that maintenance be planned properly, perhaps in conjunction with the scheduling.

2. This thesis only addresses the scheduling of the Pacific Fleet submarines. However, similar techniques can be applied to simultaneously scheduling submarines in both Atlantic and Pacific fleets. The main difficulty would be in accounting for the fact that the two fleets share certain areas of responsibility.

3. When revising a published deployment schedules, it is desirable to minimize the number of changes. In the literature, this requires a model with a persistence incentive term. For example, see Schauppner (1996), Brown, Dell and Wood (1997), and Brown, Cormican, Lawphonganich and Widdis (1997).

4. A method to solicit a ranking structure and ultimately the penalty for various unfulfilled missions will aid in providing more useful schedules with respect to the true desires of SUBPAC.

5. The cascading heuristic algorithm is the subject of an ongoing dissertation research at the Naval Postgraduate School. (Baker, 1997) When possible, results of this dissertation should be incorporated in the cascading time heuristic.

APPENDIX

This Appendix includes the data for the scheduling problem discussed in Chapter V, Section A. The first table contains the mission work-up lengths (wu_m). The next four tables provide the availability of each submarine ($avail_{m,s,t}$) for each of the four missions. Finally the specific mission requirements ($req_{t,m}$) are provided. The deployment length, d, for this data is 6 months, and the $gappen_{t,m}$ is one for all t and m.

Mission Work-up Lengths

Mission	Work-up Length (months)
0	12
I	18
II	20
III	17

Table 7 - Mission Work-up Lengths. This table provides the mission work-up lengths (wu_m).

avail$_{m,s,t}$ for $m = 0$

Submarines (s)

Months (t)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35
1	0	0	0	1	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	0	0	0	1	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
3	0	0	0	1	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
4	0	0	0	1	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
5	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
6	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
7	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
8	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
9	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
10	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
11	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
12	0	0	1	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
13	0	0	1	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1
14	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1
15	0	0	1	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
16	0	0	1	0	0	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1
17	0	0	1	0	0	1	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1	1	1	1	1	1	1
18	0	0	1	0	0	1	1	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	1	1	1	1	1
19	0	0	1	0	0	1	1	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
20	0	1	1	0	0	1	1	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
21	0	1	1	0	0	1	1	1	1	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1
22	0	1	1	0	0	1	1	1	1	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1
23	0	1	1	0	0	1	1	1	1	0	0	0	1	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1
24	0	1	1	0	0	1	1	1	1	0	0	0	1	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1
25	0	1	1	0	0	1	1	1	1	0	0	0	1	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1
26	0	1	1	0	0	0	1	1	1	0	0	0	1	1	0	1	1	0	0	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1
27	0	1	1	0	0	0	1	1	1	0	0	0	1	1	0	1	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1
28	0	1	1	0	0	0	1	1	1	0	0	0	1	1	0	1	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1
29	0	1	1	0	0	0	1	1	1	0	0	0	1	0	0	1	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1
30	0	1	1	0	0	0	1	1	1	0	0	0	1	0	0	1	1	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	1	1	1
31	0	1	1	0	0	0	1	1	1	0	0	0	1	0	1	1	1	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	1	1	1
32	0	1	1	0	0	0	1	1	1	0	0	0	1	0	1	1	1	0	0	1	1	0	1	0	0	0	0	0	0	0	0	0	0	1	1
33	0	1	1	0	0	0	1	1	1	0	0	0	1	0	1	1	1	0	1	1	1	0	1	1	0	0	0	0	0	0	0	0	0	1	1
34	0	1	0	0	0	0	1	1	1	0	0	0	1	0	1	1	1	0	1	1	1	0	1	1	0	0	0	0	0	0	0	0	0	0	1
35	0	1	0	0	0	0	1	1	1	0	0	0	1	0	1	1	1	0	1	1	1	0	1	1	0	0	0	0	0	0	0	0	0	0	1
36	0	1	0	0	0	0	1	1	1	0	0	0	1	0	1	1	1	0	1	1	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0
37	0	1	0	0	0	0	1	1	1	0	0	0	1	0	1	1	1	0	1	1	1	0	1	1	0	0	1	0	1	0	0	0	0	0	0
38	0	1	0	0	0	0	1	0	1	0	0	0	1	0	1	1	1	0	1	1	1	0	1	1	0	0	1	0	1	0	0	0	0	0	0
39	0	1	0	0	0	0	1	0	1	0	0	0	1	0	1	1	1	0	1	1	1	0	1	1	0	0	1	0	1	1	0	0	0	0	0
40	0	1	0	0	0	0	1	0	1	0	0	0	1	0	1	1	1	0	1	1	1	0	1	1	0	0	1	0	1	1	0	0	0	0	0
41	0	1	0	0	0	0	1	0	1	0	0	0	1	0	1	1	1	0	1	1	1	0	1	1	0	0	1	0	1	1	0	0	0	0	0
42	0	1	0	0	0	0	1	0	1	0	0	0	1	0	1	0	1	0	1	1	1	0	1	1	0	0	1	0	1	1	0	0	0	0	0
43	0	1	0	0	0	0	0	0	1	0	0	0	1	0	1	0	1	0	1	1	1	0	1	1	0	0	1	0	1	1	0	0	0	0	0
44	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	1	0	1	1	1	0	1	1	0	0	1	1	1	1	0	0	0	0	0
45	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	1	0	1	1	1	0	1	1	0	0	1	1	1	1	1	0	0	0	0
46	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	1	1	1	0	1	1	0	0	1	1	1	1	1	0	0	0	0
47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	1	1	1	0	1	1	0	0	1	1	1	1	1	0	0	0	0
48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	1	1	1	0	1	1	0	0	1	1	1	1	1	1	0	0	0
49	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	1	0	1	1	1	0	1	1	0	0	1	1	1	1	1	1	0	0	0
50	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	1	0	1	1	0	0	1	1	1	1	1	1	1	0	0
51	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	1	0	1	1	0	0	1	1	1	1	1	1	1	0	0
52	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	1	0	1	1	0	0	1	1	1	1	1	1	1	1	0
53	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	1	0	1	1	0	0	1	1	1	1	1	1	1	1	0
54	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	1	0	1	1	0	0	1	1	1	1	1	1	1	1	1
55	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	1	1	0	0	1	1	1	1	1	1	1	1	1
56	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	1	0	1	1	0	0	0	1	1	1	1	1	1	1	1
57	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	1	0	0	0	1	1	1	1	1	1	1	1
58	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	1	1	1	1	1	1	1	1
59	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	1	1	1	1	1	1	1	1
60	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1

Table 8 - avail$_{m,s,t}$ for m=0. This table provides the availability and compatibility data (avail$_{m,s,t}$) for all submarines over the entire time horizon and for m=0.

$\text{avail}_{m,s,t}$ for $m = \text{I}$

Submarines (s)

Months (t)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35
1	0	0	0	1	0	0	0	0	0	1	1	0	1	0	1	1	1	1	1	0	1	0	1	1	1	0	0	1	1	1	0	1	0	1	1
2	0	0	0	1	0	0	0	0	0	0	0	0	1	0	1	1	1	1	1	0	1	0	1	1	1	0	0	1	1	1	0	1	0	1	1
3	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	0	1	0	1	1	1	0	0	1	1	1	0	1	0	1	1
4	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	0	1	0	1	1	1	0	0	1	1	1	0	1	0	1	1
5	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1	0	1	1	1	0	0	1	1	1	0	1	0	1	1
6	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1	0	1	1	1	0	0	1	1	1	0	1	0	1	1
7	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	1	1	1	0	0	1	1	1	0	1	0	1	1
8	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	1	0	0	1	1	1	0	1	0	1	1
9	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	1	0	0	1	1	1	0	1	0	1	1
10	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	1	0	0	1	1	1	0	1	0	1	1
11	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	1	0	0	1	1	1	0	1	0	1	1
12	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	1	0	0	1	1	1	0	1	0	1	1
13	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	1	1	1	0	1	0	1	1
14	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	1	1	1	0	1	0	1	1
15	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	1	1	1	0	1	0	1	1
16	0	0	1	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	1	1	0	1	0	1	1
17	0	0	1	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1	0	1	1
18	0	0	1	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1	0	1	1
19	0	0	1	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	1	1
20	0	0	1	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	1	1
21	0	0	1	0	0	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1
22	0	0	1	0	0	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1
23	0	0	1	0	0	1	1	0	0	0	0	0	1	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1
24	0	0	1	0	0	1	1	0	0	0	0	0	1	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1
25	0	0	1	0	0	1	1	0	0	0	0	0	1	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1
26	0	0	1	0	0	0	1	0	0	0	0	0	1	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1
27	0	0	1	0	0	0	1	0	0	0	0	0	1	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1
28	0	0	1	0	0	0	1	0	0	0	0	0	1	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1
29	0	0	1	0	0	0	1	0	0	0	0	0	1	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1
30	0	0	1	0	0	0	1	0	0	0	0	0	1	0	0	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1
31	0	0	1	0	0	0	1	0	0	0	0	0	1	0	1	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1
32	0	0	1	0	0	0	1	0	0	0	0	0	1	0	1	1	1	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	1	1
33	0	0	1	0	0	0	1	0	0	0	0	0	1	0	1	1	1	0	1	0	1	0	1	1	0	0	0	0	0	0	0	0	0	1	1
34	0	0	0	0	0	0	1	0	0	0	0	0	1	0	1	1	1	0	1	0	1	0	1	1	0	0	0	0	0	0	0	0	0	0	1
35	0	0	0	0	0	0	1	0	0	0	0	0	1	0	1	1	1	0	1	0	1	0	1	1	0	0	0	0	0	0	0	0	0	0	1
36	0	0	0	0	0	0	1	0	0	0	0	0	1	0	1	1	1	0	1	0	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0
37	0	0	0	0	0	0	1	0	0	0	0	0	1	0	1	1	1	0	1	0	1	0	1	1	0	0	0	0	1	0	0	0	0	0	0
38	0	0	0	0	0	0	1	0	0	0	0	0	1	0	1	1	1	0	1	0	1	0	1	1	0	0	0	0	1	0	0	0	0	0	0
39	0	0	0	0	0	0	1	0	0	0	0	0	1	0	1	1	1	0	1	0	1	0	1	1	0	0	0	0	1	1	0	0	0	0	0
40	0	0	0	0	0	0	1	0	0	0	0	0	1	0	1	1	1	0	1	0	1	0	1	1	0	0	0	0	1	1	0	0	0	0	0
41	0	0	0	0	0	0	1	0	0	0	0	0	1	0	1	1	1	0	1	0	1	0	1	1	0	0	0	0	1	1	0	0	0	0	0
42	0	0	0	0	0	0	1	0	0	0	0	0	1	0	1	0	1	0	1	0	1	0	1	1	0	0	0	0	1	1	0	0	0	0	0
43	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	1	0	1	0	1	0	1	1	0	0	0	0	1	1	0	0	0	0	0
44	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	1	0	1	0	1	0	1	1	0	0	0	1	1	1	0	0	0	0	0
45	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	1	0	1	0	1	0	1	1	0	0	0	1	1	1	0	0	0	0	0
46	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	1	0	1	0	1	1	0	0	0	1	1	1	0	0	0	0	0
47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	1	0	1	0	1	1	0	0	0	1	1	1	0	0	0	0	0
48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	1	0	1	0	1	1	0	0	0	1	1	1	0	1	0	0	0
49	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	1	0	1	0	1	0	1	1	0	0	0	1	1	1	0	1	0	0	0
50	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	1	0	1	1	0	0	0	1	1	1	0	1	0	0	0
51	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	1	0	1	1	0	0	0	1	1	1	0	1	0	0	0
52	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	1	0	1	1	0	0	0	1	1	1	0	1	0	1	0
53	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	1	0	1	1	0	0	0	1	1	1	0	1	0	1	0
54	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	1	0	1	1	0	0	0	1	1	1	0	1	0	1	1
55	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	1	1	0	0	0	1	1	1	0	1	0	1	1
56	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	1	1	0	0	0	1	1	1	0	1	0	1	1
57	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	1	1	1	0	1	0	1	1
58	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	1	1	0	1	0	1	1
59	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	1	1	0	1	0	1	1
60	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	1	0	1	1

Table 9 - $\text{avail}_{m,s,t}$ for m=I. This table provides the availability and compatibility data ($\text{avail}_{m,s,t}$) for all submarines over the entire time horizon and for m=I.

$avail_{m,s,t}$ for m = II

Submarines (s)

Months (t)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35
1	0	0	0	0	0	0	0	0	0	1	1	1	0	1	1	0	0	0	1	1	0	1	0	1	1	1	1	1	0	1	1	1	1	0	1
2	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	1	1	0	1	0	1	1	1	1	1	0	1	1	1	1	0	1
3	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	1	1	0	1	0	1	1	1	1	1	0	1	1	1	1	0	1
4	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	1	1	0	1	0	1	1	1	1	1	0	1	1	1	1	0	1
5	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	1	0	1	0	1	1	1	1	1	0	1	1	1	1	0	1
6	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	1	0	1	0	1	1	1	1	1	0	1	1	1	1	0	1
7	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	1	0	1	1	1	1	1	0	1	1	1	1	0	1
8	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	1	1	1	1	1	0	1	1	1	1	0	1
9	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	1	1	1	1	1	0	1	1	1	1	0	1
10	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	1	1	1	1	1	0	1	1	1	1	0	1
11	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	1	1	1	1	1	0	1	1	1	1	0	1
12	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	1	1	1	1	1	0	1	1	1	1	0	1
13	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	1	1	1	1	1	0	1	1	1	1	0	1
14	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	1	1	1	1	1	0	1	1	1	1	0	1
15	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	1	1	1	1	0	1	1	1	1	0	1
16	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	1	1	1	1	0	1
17	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	1	1	1	1	0	1
18	0	0	0	0	0	0	0	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	1	1	1	0	1
19	0	0	0	0	0	0	0	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	1
20	0	1	0	0	0	0	0	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	1
21	0	1	0	0	0	0	0	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	1
22	0	1	0	0	0	0	0	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	1
23	0	1	0	0	0	0	0	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	1
24	0	1	0	0	0	0	0	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	1
25	0	1	0	0	0	0	0	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	1
26	0	1	0	0	0	0	0	1	1	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	1	1	0	1
27	0	1	0	0	0	0	0	1	1	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1
28	0	1	0	0	0	0	0	1	1	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1
29	0	1	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1
30	0	1	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
31	0	1	0	0	0	0	0	1	1	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
32	0	1	0	0	0	0	0	1	1	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
33	0	1	0	0	0	0	0	1	1	0	0	0	0	0	1	0	0	0	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1
34	0	1	0	0	0	0	0	1	1	0	0	0	0	0	1	0	0	0	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1
35	0	1	0	0	0	0	0	1	1	0	0	0	0	0	1	0	0	0	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1
36	0	1	0	0	0	0	0	1	1	0	0	0	0	0	1	0	0	0	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
37	0	1	0	0	0	0	0	1	1	0	0	0	0	0	1	0	0	0	1	1	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0
38	0	1	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	1	1	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0
39	0	1	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	1	1	0	0	0	1	0	0	1	0	0	1	0	0	0	0	0
40	0	1	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	1	1	0	0	0	1	0	0	1	0	0	1	0	0	0	0	0
41	0	1	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	1	1	0	0	0	1	0	0	1	0	0	1	0	0	0	0	0
42	0	1	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	1	1	0	0	0	1	0	0	1	0	0	1	0	0	0	0	0
43	0	1	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	1	1	0	0	0	1	0	0	1	0	0	1	0	0	0	0	0
44	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	1	0	0	0	1	0	0	1	1	0	1	0	0	0	0	0
45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	1	0	0	0	1	0	0	1	1	0	1	1	0	0	0	0
46	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	1	0	0	0	1	0	0	1	1	0	1	1	0	0	0	0
47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	1	0	0	0	1	0	0	1	1	0	1	1	0	0	0	0
48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	1	0	0	0	1	0	0	1	1	0	1	1	1	0	0	0
49	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	1	0	0	0	1	0	0	1	1	0	1	1	1	0	0	0
50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	1	0	0	1	1	0	1	1	1	1	0	0
51	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	1	0	0	1	1	0	1	1	1	1	0	0
52	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	1	0	0	1	1	0	1	1	1	1	0	0
53	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	1	0	0	1	1	0	1	1	1	1	0	0
54	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	1	0	0	1	1	0	1	1	1	1	0	1
55	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	1	1	0	1	1	1	1	0	1
56	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	1	0	1	1	1	1	0	1
57	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	1	1	1	1	0	1
58	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	1	1	1	1	0	1
59	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	1	1	1	1	0	1
60	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	1	1	0	1

Table 10 - $avail_{m,s,t}$ for m=II. This table provides the availability and compatibility data ($avail_{m,s,t}$) for all submarines over the entire time horizon and for m=II.

$avail_{m,s,t}$ for m = III

Submarines (s)

Months (t)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35
1	0	0	0	0	0	0	0	0	0	0	1	1	0	1	0	0	0	0	0	1	0	1	0	1	1	1	1	0	0	1	1	0	1	1	1
2	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	1	0	1	1	1	1	0	0	1	1	0	1	1	1
3	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	1	0	1	1	1	1	0	0	1	1	0	1	1	1
4	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	1	0	1	1	1	1	0	0	1	1	0	1	1	1
5	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	1	0	1	1	1	1	0	0	1	1	0	1	1	1
6	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	1	0	1	1	1	1	0	0	1	1	0	1	1	1
7	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	1	0	1	1	1	1	0	0	1	1	0	1	1	1
8	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	1	1	1	1	0	0	1	1	0	1	1	1
9	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	1	1	1	1	0	0	1	1	0	1	1	1
10	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	1	1	1	1	0	0	1	1	0	1	1	1
11	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	1	1	1	1	0	0	1	1	0	1	1	1
12	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	1	1	1	1	0	0	1	1	0	1	1	1
13	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	1	1	1	1	0	0	1	1	0	1	1	1
14	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	1	1	1	1	0	0	1	1	0	1	1	1
15	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	1	1	0	1	1	1
16	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	1	1	0	1	1	1
17	0	0	0	0	0	1	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	1	1	0	1	1	1
18	0	0	0	0	0	1	0	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	1	0	1	1	1
19	0	0	0	0	0	1	0	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1	1	1
20	0	1	0	0	0	1	0	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1	1	1
21	0	1	0	0	0	1	0	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	1
22	0	1	0	0	0	1	0	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	1
23	0	1	0	0	0	1	0	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	1
24	0	1	0	0	0	1	0	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	1
25	0	1	0	0	0	1	0	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	1
26	0	1	0	0	0	0	0	1	1	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	1	1	1
27	0	1	0	0	0	0	0	1	1	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1
28	0	1	0	0	0	0	0	1	1	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1
29	0	1	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1
30	0	1	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1
31	0	1	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1
32	0	1	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
33	0	1	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	1	1
34	0	1	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1
35	0	1	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1
36	0	1	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
37	0	1	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0
38	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0
39	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	1	0	0	1	0	0	0	0	0
40	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	1	0	0	1	0	0	0	0	0
41	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	1	0	0	1	0	0	0	0	0
42	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	1	0	0	1	0	0	0	0	0
43	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	1	0	0	1	0	0	0	0	0
44	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	1	0	0	1	0	0	0	0	0
45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	1	0	0	1	1	0	0	0	0
46	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	1	0	0	1	1	0	0	0	0
47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	1	0	0	1	1	0	0	0	0
48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	1	0	0	1	1	0	0	0	0
49	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	1	0	0	1	1	0	0	0	0
50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	1	1	0	1	0	0
51	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	1	1	0	1	0	0
52	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	1	1	0	1	1	0
53	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	1	1	0	1	1	0
54	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	1	1	0	1	1	1
55	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	1	1	0	1	1	1
56	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	1	0	1	1	1
57	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	1	0	1	1	1
58	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	1	0	1	1	1
59	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	1	0	1	1	1
60	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1	1	1

Table 11 - $avail_{m,s,t}$ for m=III. This table provides the availability and compatibility data ($avail_{m,s,t}$) for all submarines over the entire time horizon and for m=III.

Mission Requirements

	Missions (m)			
Months (t)	0	I	II	III
1	6	1	2	0
2	6	1	2	0
3	6	1	2	0
4	6	1	2	0
5	6	1	2	0
6	6	1	2	0
7	6	1	2	0
8	6	1	2	0
9	6	1	2	1
10	6	1	2	1
11	6	1	2	1
12	6	1	2	1
13	6	1	2	1
14	6	1	2	1
15	6	1	2	0
16	6	1	2	0
17	6	1	2	0
18	6	1	2	0
19	6	1	2	0
20	6	1	2	0
21	6	1	2	0
22	6	1	2	0
23	6	1	2	0
24	6	1	2	0
25	6	1	2	0
26	6	1	2	0
27	6	1	2	0
28	6	1	2	0
29	6	1	2	0
30	6	1	2	0
31	6	1	2	0
32	6	1	2	0
33	6	1	2	0
34	6	1	2	1
35	6	1	2	1
36	6	1	2	1
37	6	1	2	1
38	6	1	2	1
39	6	1	2	1
40	6	1	2	0
41	6	1	2	0
42	6	1	2	0
43	6	1	2	0
44	6	1	2	0
45	6	1	2	0
46	6	1	2	0
47	6	1	2	0
48	6	1	2	0
49	6	1	2	0
50	6	1	2	0
51	6	1	2	0
52	6	1	2	0
53	6	1	2	0
54	6	1	2	0
55	6	1	2	0
56	6	1	2	0
57	6	1	2	0
58	6	1	2	0
59	6	1	2	0
60	6	1	2	0

Table 12 - Mission Requirements over Time. This table provides the requirements ($req_{t,m}$) for all missions over the time horizon.

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